VOLTAGE REGULATOR

Lecture 11

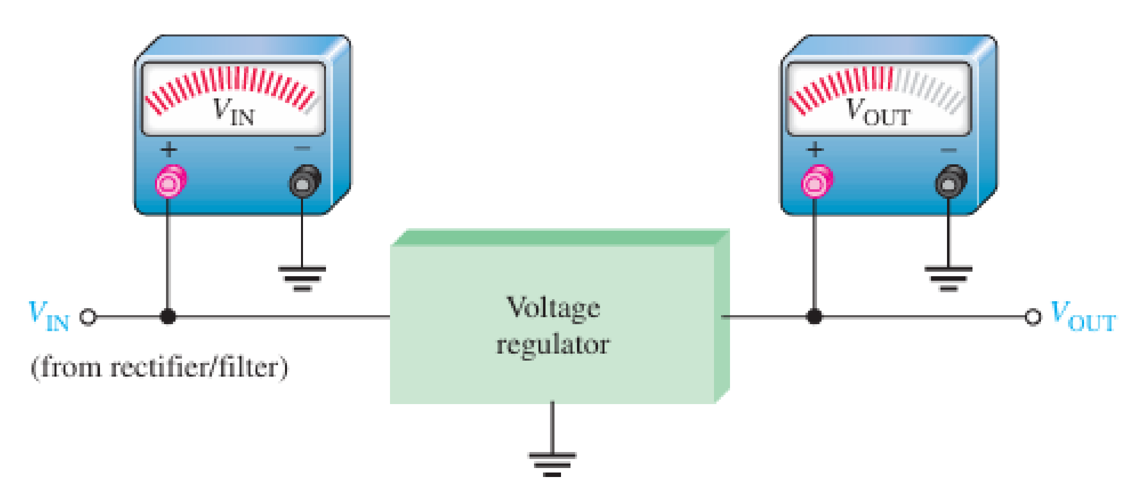
OVERVIEW

- Voltage Regulation
- Basic Linear Series Regulators
- Basic Linear Shunt Regulators
- Basic Switching Regulators
- Integrated Circuit Voltage Regulators

VOLTAGE REGULATION

Two basic categories of voltage regulation:

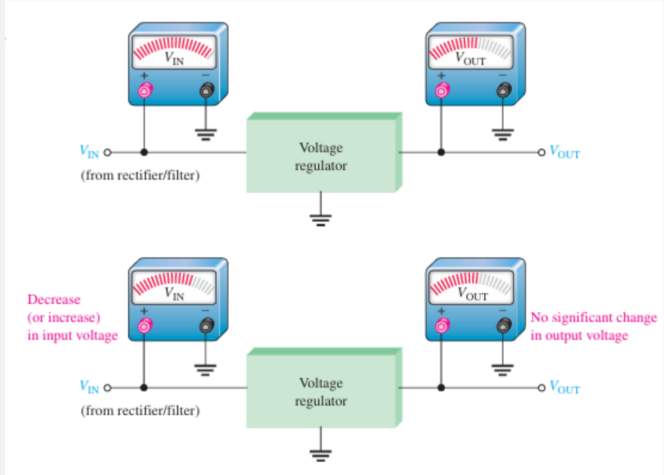
- **Line Regulation** – maintain a nearly constant output voltage when the input voltage varies.
- **Load Regulation** – maintain a nearly constant output voltage when the load varies.



LINE REGULATION

- When the AC input (line) voltage of a power supply changes, an electronic circuit called a regulator maintains a nearly constant output voltage. Line regulation can be defined as the percentage change in the output voltage for a given change in the input voltage. When taken over a range of input voltage values, line regulation is expressed as a percentage by the following formula:

$$Line\ regulation = \left(\frac{\Delta V_{OUT}}{\Delta V_{in}}\right)100\%$$



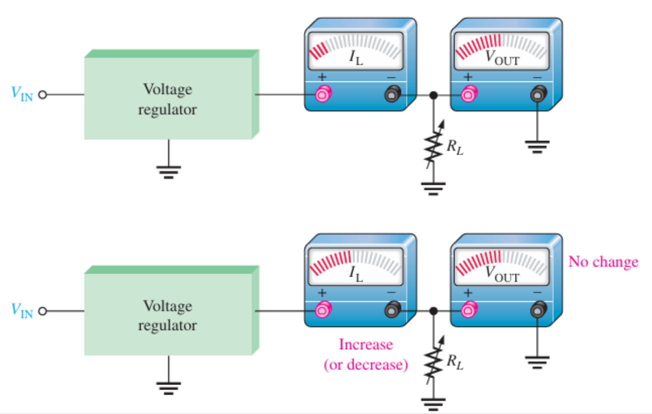
- Line regulation can also be expressed in units of %/V. For example, a line regulation of 0.05%/V means that the output voltage changes 0.05 percent when the input voltage in increases or decreases by one Volt. Line regulation can be calculated using the following formula:

$$Line\ regulation = \left(\frac{\Delta V_{OUT}/V_{OUT}}{\Delta V_{in}}\right)100\%$$

LOAD REGULATION

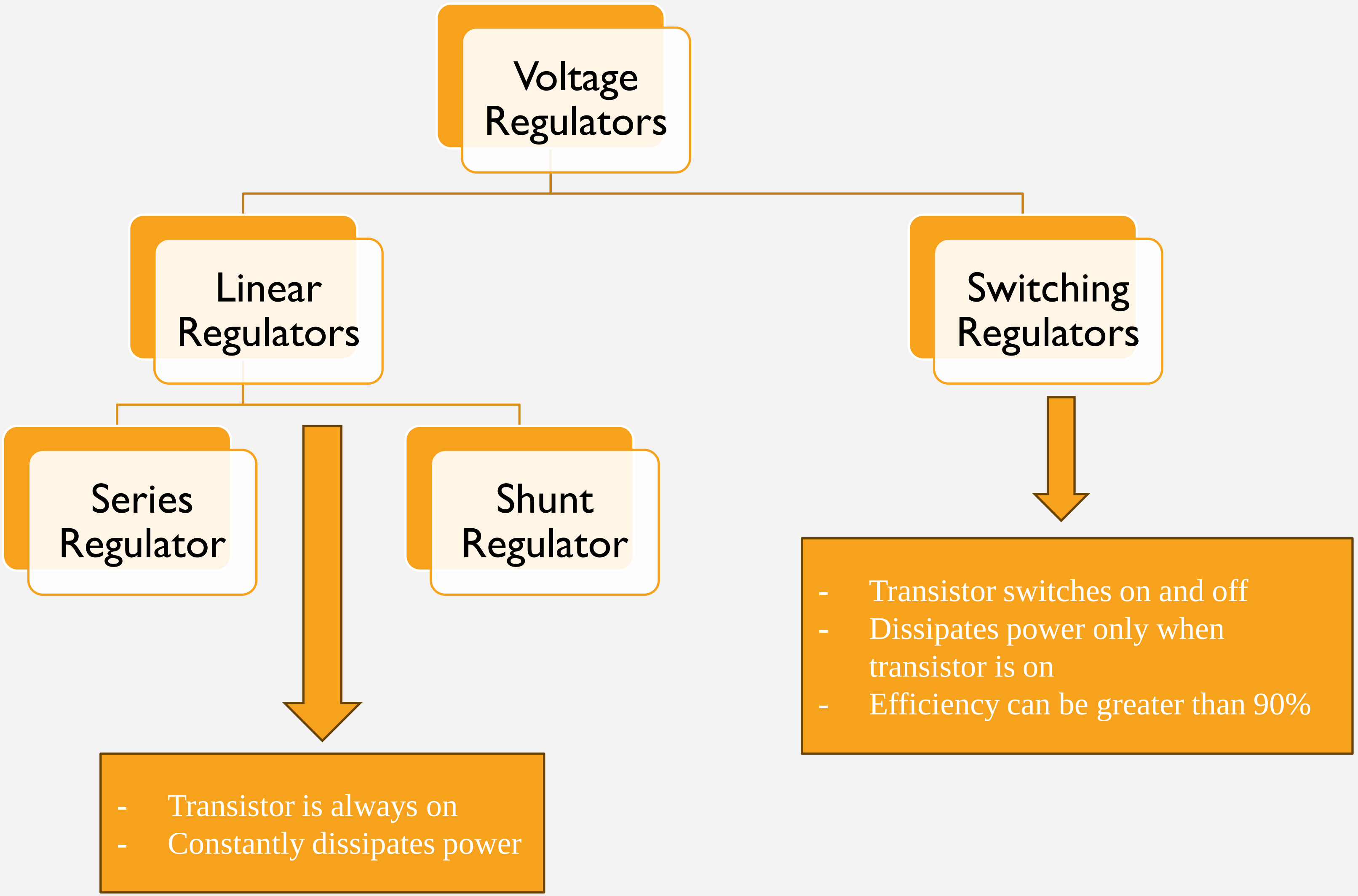
- When the amount of current through a load changes due to a varying load resistance, the voltage regulator must maintain a nearly constant output voltage across the load.
- A change in load current has practically no effect on the output voltage of a regulator (within certain limits).
- **Load regulation** can be defined as the percentage change in output voltage for a given change in load current. One way to express load regulation is as a percentage change in output voltage from no-load (NL) to full-load (FL):

$$Load\ regulation = \left(\frac{V_{NL} - V_{FL}}{V_{FL}}\right)100\%$$



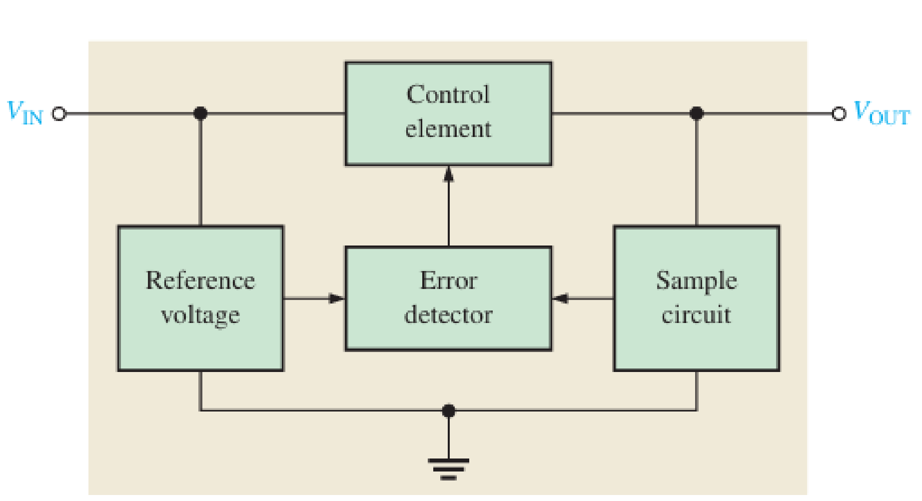
- Alternately, the load regulation can be expressed as a percentage change in output voltage for each mA change in load current. For example, a load regulation of $0.01\%/mA$ means that the output voltage changes 0.01 percent when the load current increases or decreases 1 mA.

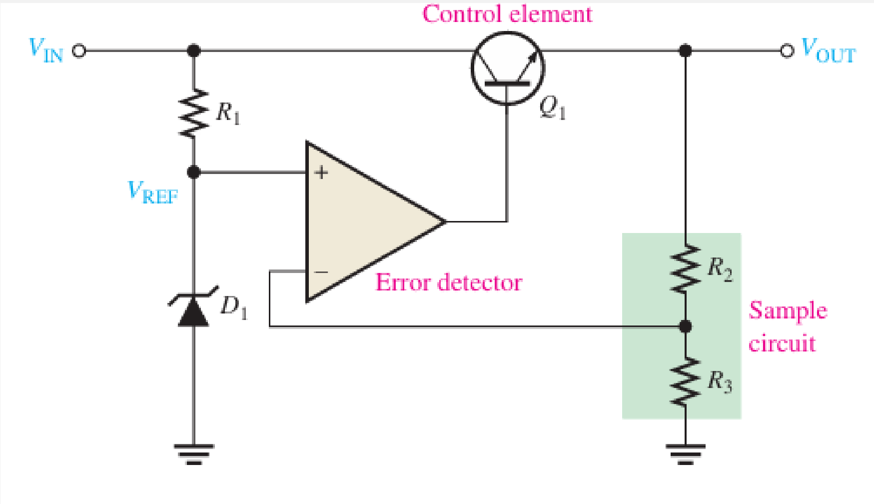
BASIC LINEAR SERIES REGULATORS



SERIES REGULATOR

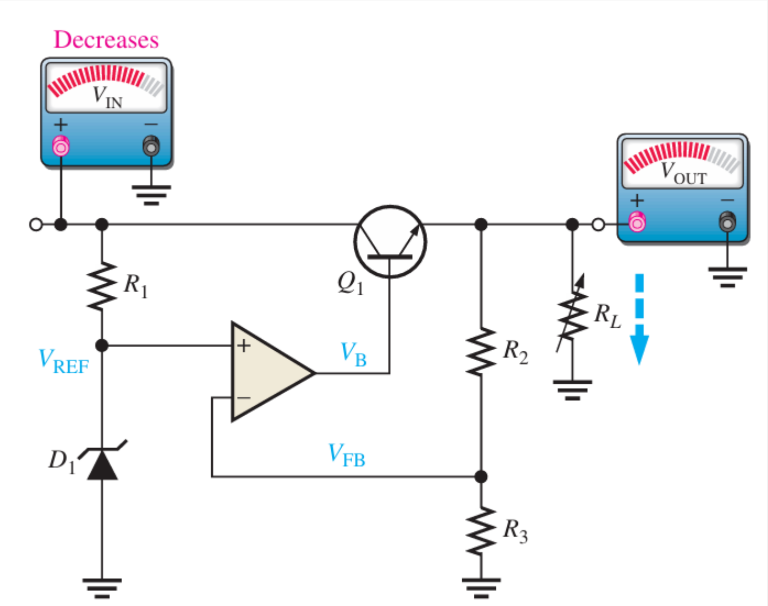
- The control element is a pass transistor in series with the load between the input and output.
- The output sample circuit senses a change in the output voltage.
- The error detector compares the sample voltage with a reference voltage and causes the control element to compensate in order to maintain a constant output voltage.





SERIES REGULATOR

- The resistive voltage divider formed by R_2 and R_3 senses any change in the output voltage.
- When the output tries to decrease because of a decrease in V_{IN} or because of an increase in I_L caused by a decrease in R_L, a proportional voltage decrease is applied to the op-amp's inverting input by the voltage divider.
- Since the zener diode (D_1) holds the other op-amp input at a nearly constant reference voltage, V_{REF}, a small difference voltage (error voltage) is developed across the op-amp's inputs. This difference voltage is amplified, and the op-amp's output voltage, V_B, increases.
- This increase is applied to the bas of Q_1, causing emitter voltage V_{OUT} to increase until the voltage to the inverting input again equals the reference (zener) voltage.



SERIES REGULATOR

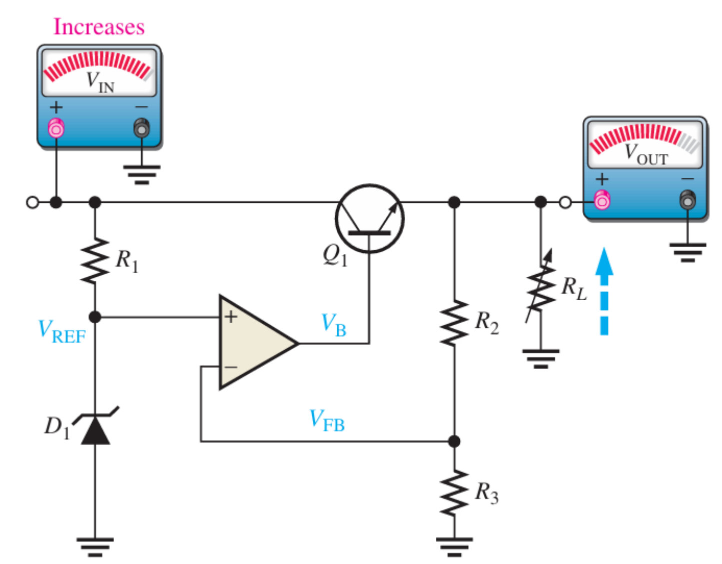
- The op-amp in the series regulator is actually connected as a noninverting amplifier where the reference voltage V_{REF} is the input at the noninverting terminal, and the R_2/R_3 voltage divider forms the negative feedback circuit. The closed-loop voltage gain is:

$$A_{cl} = 1 + \frac{R_2}{R_3}$$

- Therefore, the regulated output voltage of the series regulator (neglecting the base-emitter voltage of Q_1) is

$$V_{OUT} \cong \left(1 + \frac{R_2}{R_3}\right) V_{REF}$$

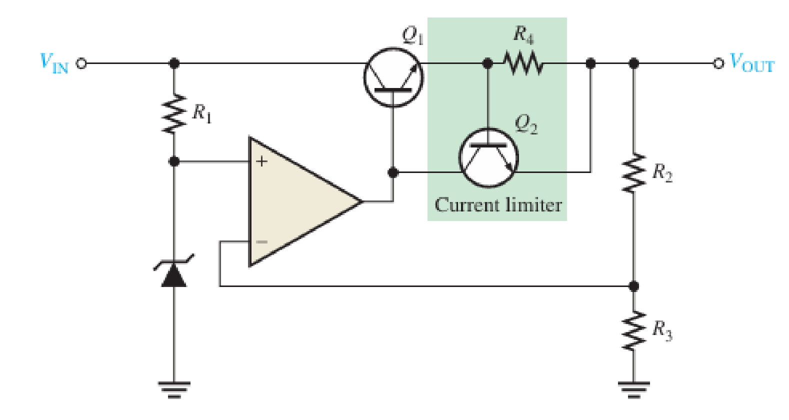
- The output voltage is determined by the zener voltage and the resistors R_2 and R_3.
- The output voltage is relatively independent of the input voltage, and therefore, regulation is achieved (as long as the input voltage and load current are within the specified limits.
- When V_{IN} or R_L increases, V_{OUT} attempts to increase.
- The feedback voltage, V_{FB}, also attempts to increase, and as a result, V_B, applied to the base of the control transistor, attempts to decrease, thus compensating for the attempted increase in V_{OUT} by decreasing the Q_1 emitter voltage.
- When V_{IN} (or R_L) stabilizes at its new higher value, the voltages return to their original values, thus keeping VOUT constant as a result of the negative feedback.



SHORT CIRCUIT OR OVERLOAD PROTECTION

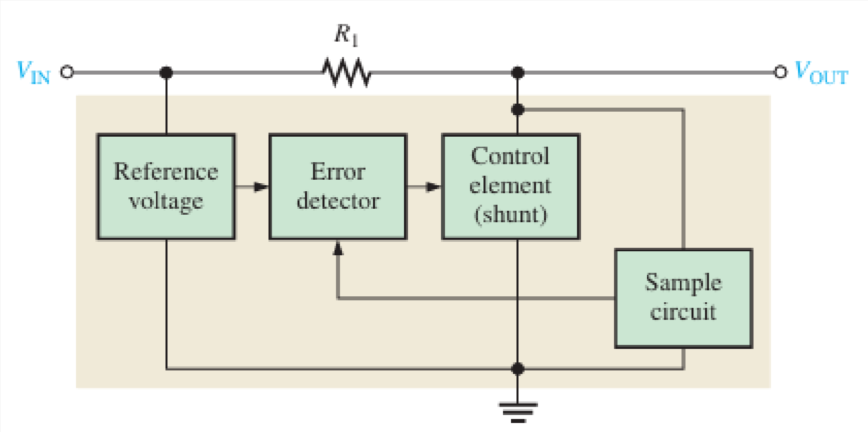
- If an excessive amount of load current is drawn, the series-pass transistor can be quickly damaged or destroyed.
- Most regulators use some type of excess current protection in the form of a current-limiting mechanism.
- The current-limiting circuit consists of transistor Q_2 and resistor R_4.
- The load current through R_4 produces a voltage from base to emitter of reaches a predetermined maximum value, the voltage drop across R_4 is sufficient to forward-bias the base-emitter junction of Q_2, thus causing it to conduct.
- Enough op-amp output current is diverted through Q_2, to reduce the Q_1 base current, so that I_L is limited to its maximum value, $I_{L(\max)}$.
- Since the base-to-emitter voltage of $Q2$, cannot exceed approximately $0.7\ V$, the voltage across R_4 is held to this value, and the load current is limited to

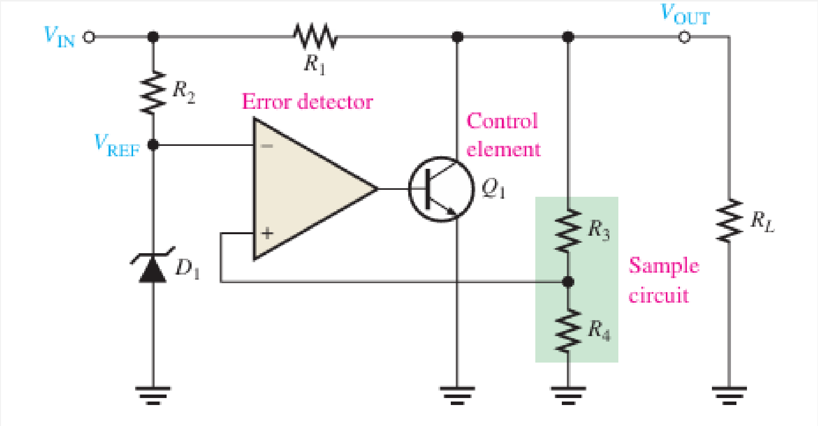
$$I_{L(\max)} = \frac{0.7\ V}{R_4}$$



SHUNT REGULATORS

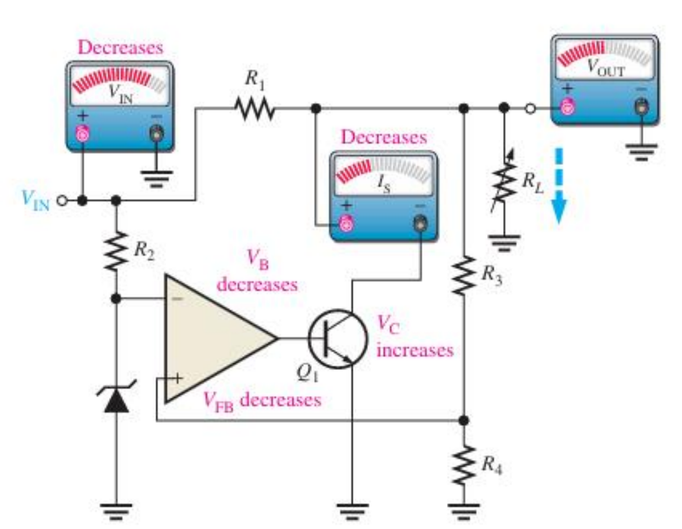
- The control element is a transistor, Q_1, in parallel with the load.
- A resistor, R_1, is in series with the load.





SHUNT REGULATORS

- The operation of the circuit is similar to that of the series regulator, except that regulation is achieved by controlling the current through the parallel transistor Q_1.
- When the output voltage tries to decrease due to a change in input voltage or load current caused by a change in load resistance, the attempted decrease is sensed by R_3 and R_4 and applied to the op-amp's noninverting input.
- The resulting difference voltage reduces the op-amp's output (V_B), driving Q_1 less, thus reducing its collector current (shunt current) and increasing the collector voltage. Thus, the original decrease in voltage is compensated for by this increase, keeping the output nearly constant.



(a) Response to a decrease in V_{IN} or R_L

SHUNT REGULATORS

- The opposite action occurs when the output tries to increase.
- With I_L and V_{OUT} constant, a change in the input voltage produces a change in shunt current (I_S) as follows:

$$\Delta I_S = \frac{\Delta V_{IN}}{R_1}$$

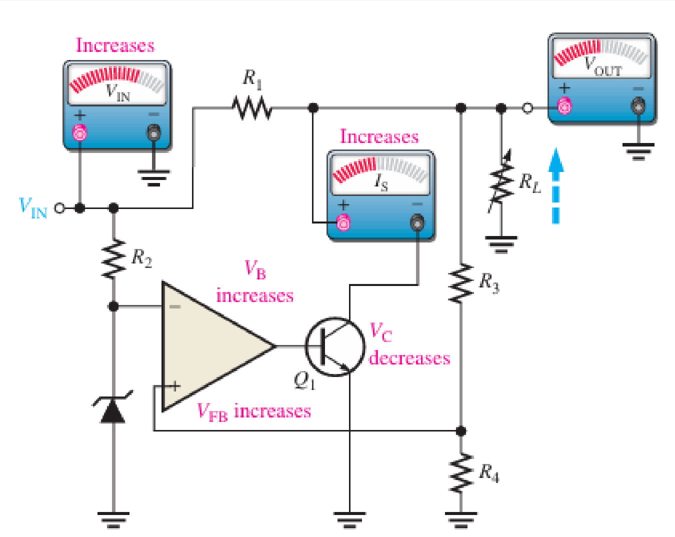
- With a constant V_{IN} and V_{OUT}, a change in load current causes an opposite change in shunt
- current. If I_L increases, I_S decreases, and vice versa.

$$\Delta I_S = -\Delta I_L$$

- The shunt regulator is less efficient than the series type but offers inherent short-circuit protection.

- If the output is shorted ($V_{OUT} = 0$), the load current is limited by the series resistor R_1 to a maximum value as follows ($I_S = 0$).

$$I_{L(max)} = \frac{V_{IN}}{R_1}$$



BASIC SWITCHING REGULATORS

- Switching regulators are designed for various power levels.
- They range in power levels from less than one watt for some battery-operated portable equipment to hundreds and thousands of watts in major applications.
- The requirements for the application determine the particular design, but all switching regulators require feedback to control the on-off time for the switch.

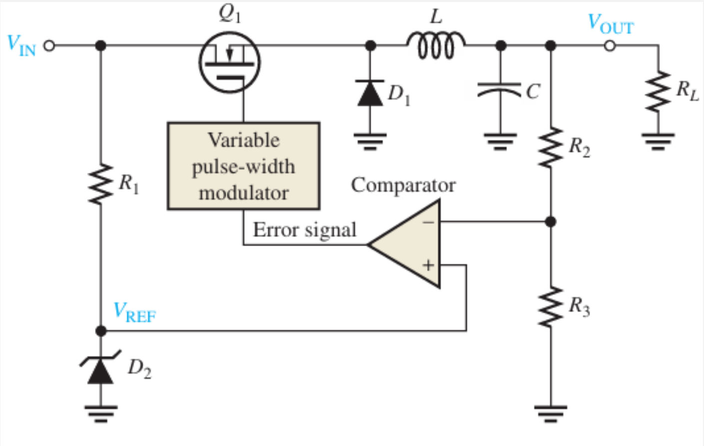
- Three basic configurations of switching regulators are
  - Step-down,
  - Step-up
  - Inverting

- In some cases, such as a laptop computer, all three types may be employed for various parts of the system; for example, the display typically will use an inverting type, the microprocessor would use a step-down type, and the disk drive may use a step-up type.

STEP-DOWN CONFIGURATION

- In the step-down configuration (also called a *buck converter*), the output voltage is always less than the input voltage.
- The basic control element is a high-speed switch, which opens and closes rapidly from a control circuit that senses the output, and it adjusts the on-time and the off-time to keep the desired output.
- When the switch is closed, the diode is off and the magnetic field of the inductor builds, storing energy.
- When the switch opens, the magnetic field collapses, keeping nearly constant current in the load.
- A path for the load current is provided through the forward-biased diode (as long as the load resistance is not too large).
- The capacitor smoothes the DC to a nearly constant level.

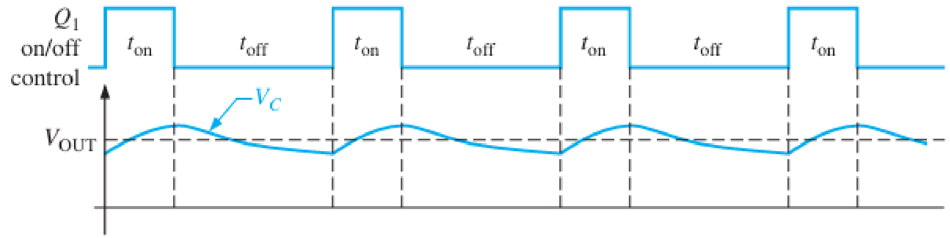
- Figure shows a basic step-down switching regulator using a D-MOSFET switching transistor.
- MOSFET transistors can switch faster than BJTs and have been improved in recent years, so they have become the preferred type of switching device, provided that the off-state voltage is not too high.



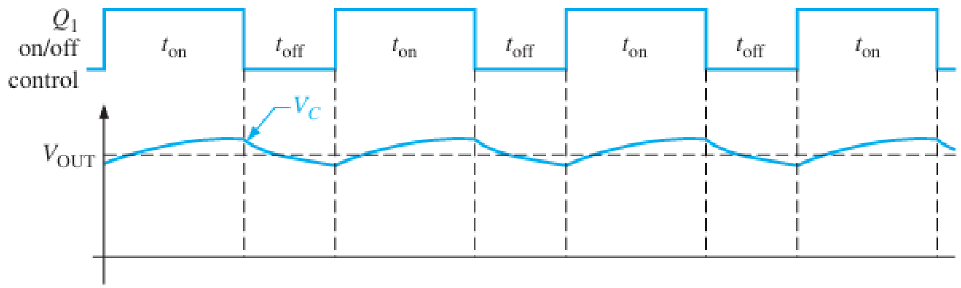
SWITCHING REGULATOR WAVEFORMS

- The V_C waveform is shown for no inductive filtering to illustrate the charge and discharge action (ripple).

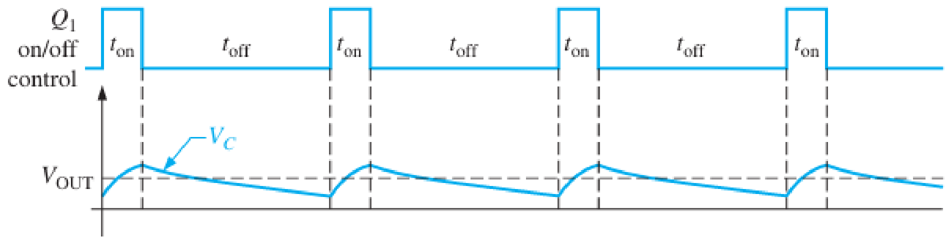
- L and C smooth V_C to a nearly constant level, as indicated by the dashed line for V_{OUT}.



(a) V_{OUT} depends on the duty cycle.



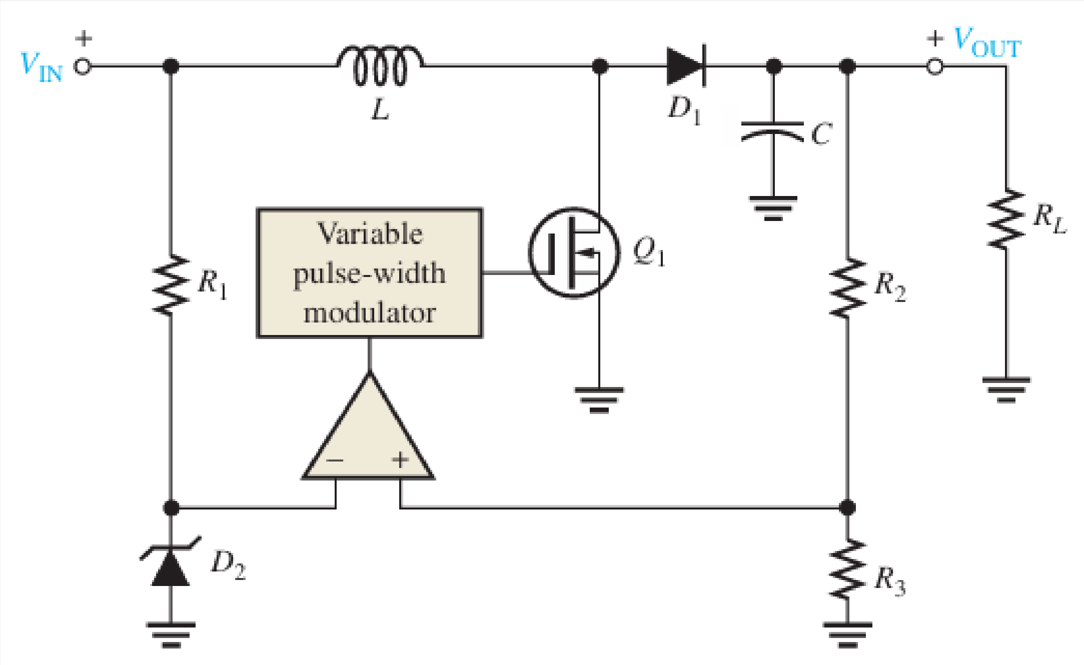
(b) Increase the duty cycle and V_{OUT} increases.



(c) Decrease the duty cycle and V_{OUT} decreases.

STEP-UP CONFIGURATION

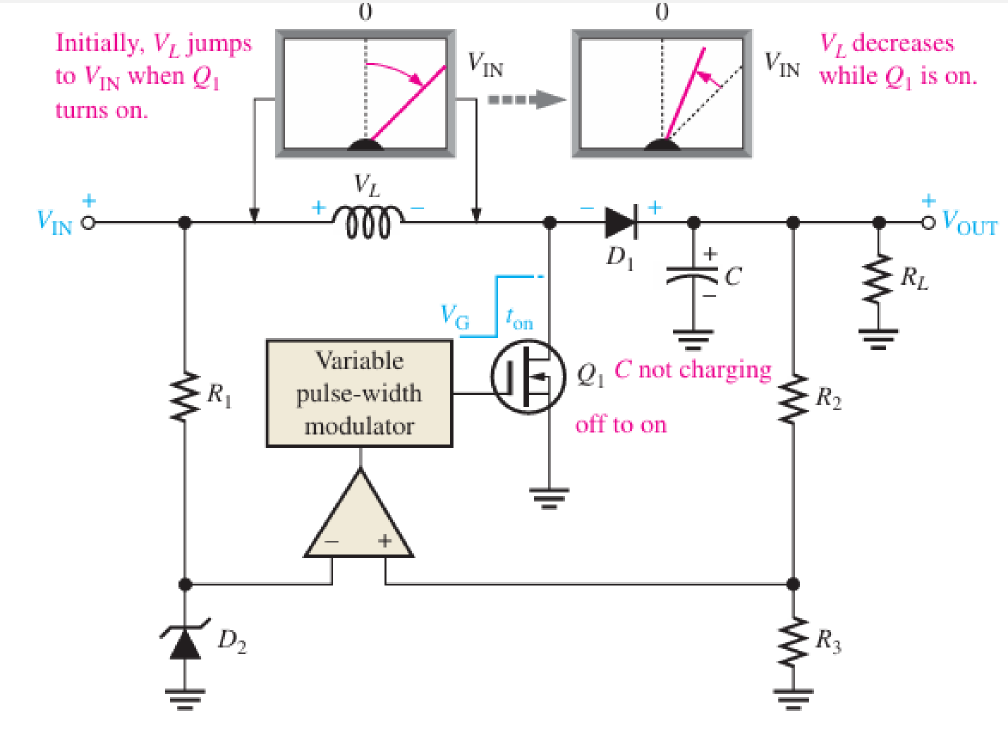
- A basic step-up type of switching regulator (sometimes called a *boost converter*) is shown in Figure below, where transistor Q_1 operates as a switch to ground.

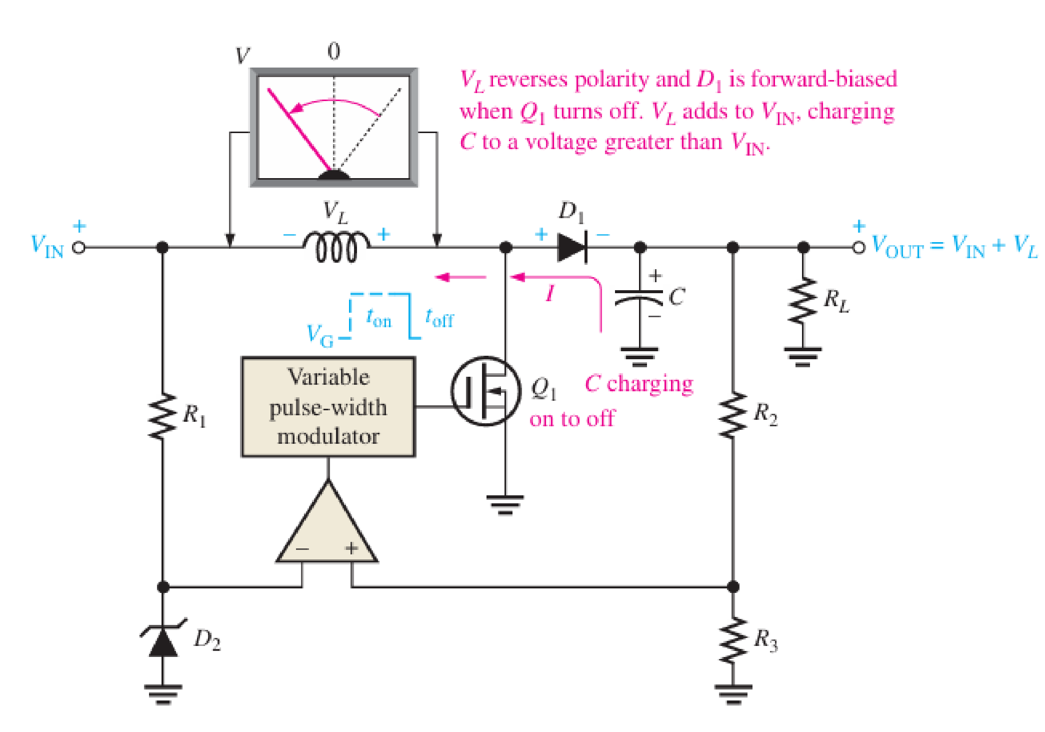


STEP-UP CONFIGURATION

- When Q_1 turns on, a voltage equal to approximately V_{IN} is induced across the inductor with a polarity.
- During the on-time (t_{on}) of Q_1, the inductor voltage, V_L, decreases from its initial maximum and diode D_1 is reverse-biased.
- The longer Q_1 is on, the smaller V_L becomes.
- During the on-time, the capacitor only discharges an extremely small amount through the load.
- When Q_1 turns off, the inductor voltage suddenly reverses polarity and adds to V_{IN}, forward-biasing diode D_1 and allowing the capacitor to charge.
- The output voltage is equal to the capacitor voltage and can be larger than V_{IN} because the capacitor is charged to V_{IN} plus the voltage induced across the inductor during the off-time of Q_1.
- The output voltage is dependent on both the inductor's magnetic field action (determined by t_{on}) and the charging of the capacitor (determined by t_{off}).
- Voltage regulation is achieved by the variation of the on-time of Q_1 (within certain limits) as related to changes in V_{OUT} due to changing load or input voltage.
- If V_{OUT} tries to increase, the on-time of Q_1 will decrease, resulting in a decrease in the amount that C will charge.
- If V_{OUT} tries to decrease, the on-time of Q_1 will increase, resulting in an increase in the amount that C will charge. This regulating action maintains V_{OUT} at an essentially constant level.

STEP-UP CONFIGURATION

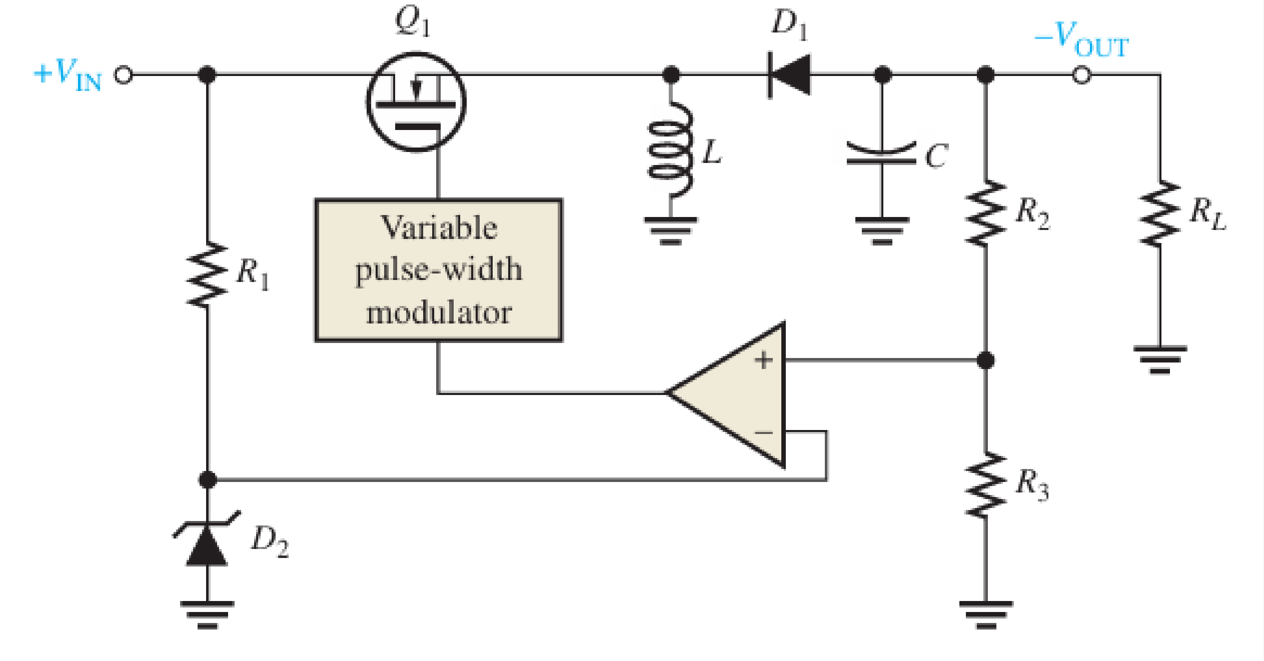




VOLTAGE-INVERTER CONFIGURATION

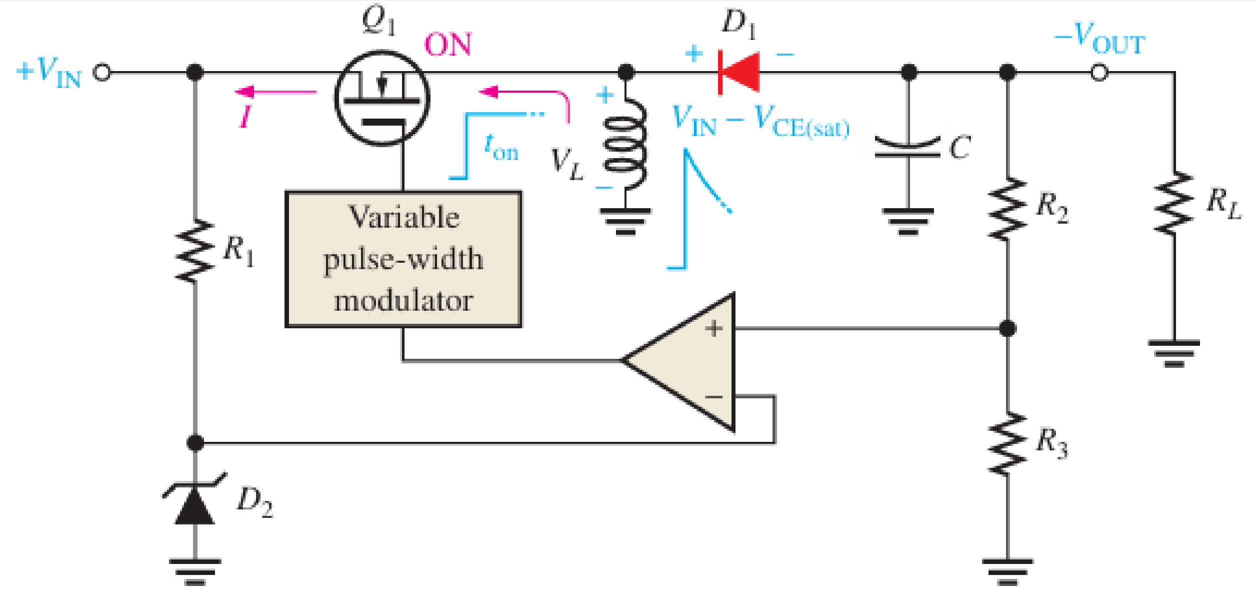
- Produces an output voltage that is opposite in polarity to the input.

- Sometimes called a *buck-boost* converter.



VOLTAGE-INVERTER CONFIGURATION

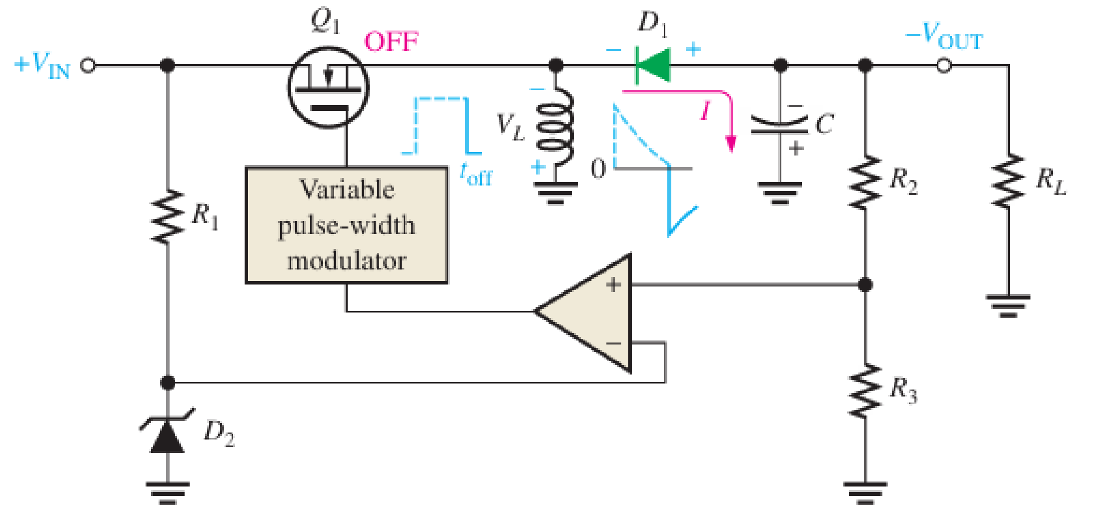
- When Q_1 turns on, the inductor voltage jumps to approximately $V_{IN} - V_{CE(sat)}$ and the magnetic field rapidly expands, as shown.
- While Q_1 is on, the diode is reverse-biased and the inductor voltage decreases from its initial maximum.



(a) When Q_1 is on, D_1 is reverse-biased.

VOLTAGE-INVERTER CONFIGURATION

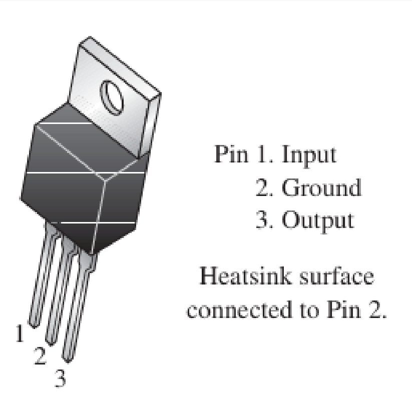
- When Q_1 turns off, the magnetic field collapses and the inductor's polarity reverses.
- This forward-biases the diode, charges C, and produces a negative output voltage, as indicated.
- The repetitive on-off action of Q_1 produces a repetitive charging and discharging that is smoothed by the LC filter action.



(b) When Q_1 turns off, D_1 forward biases.

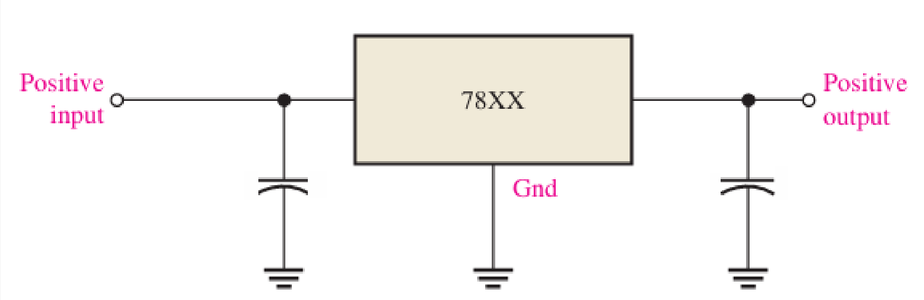
INTEGRATED CIRCUIT VOLTAGE REGULATORS

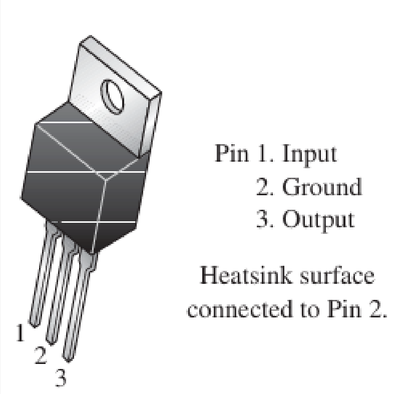
- Several types of both linear and switching regulators are available in integrated circuit (IC) form.
- Generally, the linear regulators are three-terminal devices that provide either positive or negative output voltages that can be either fixed or adjustable.



FIXED POSITIVE LINEAR VOLTAGE REGULATORS

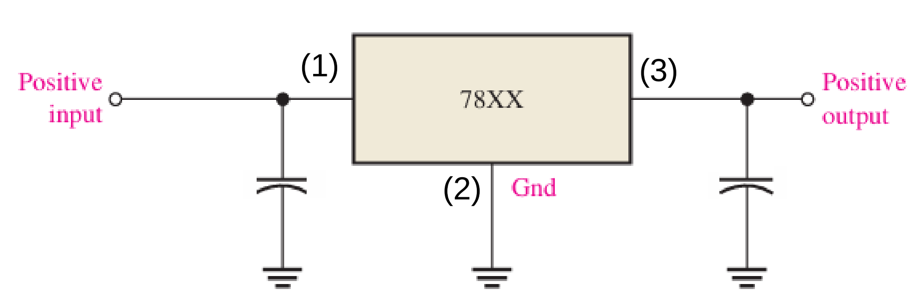
- 78XX series of IC regulators is representative of three-terminal devices that provide a fixed positive output voltage.
- The three terminals are input, output, and ground as indicated in the standard fixed voltage configuration
- The last two digits in the part number designate the output voltage. For example, the 7805 is a +5.0 V
- For any given regulator, the output voltage can be as much as 4% of the nominal output.
- regulator. For any given regulator, the output voltage can
- A 7805 may have an output from 4.8 V to 5.2 V but will remain constant in that range.





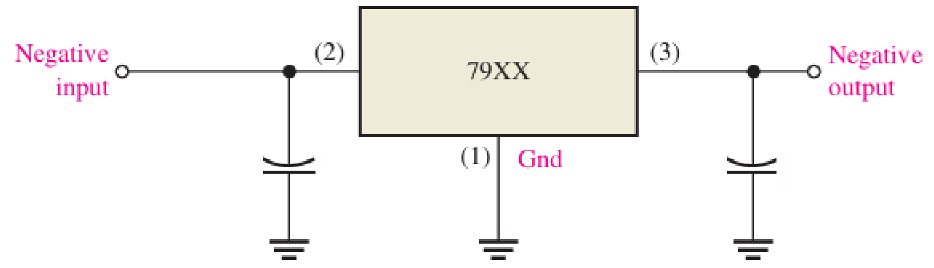
FIXED POSITIVE LINEAR VOLTAGE REGULATORS

- Capacitors, although not always necessary, are sometimes used on the input and output.
- The output capacitor acts basically as a line filter to improve transient response.
- The input capacitor filters the input and prevents unwanted oscillations when the regulator is some distance from the power supply filter such that the line has a significant inductance.
- The 78XX series can produce output currents up to in excess of 1 A when used with an adequate heat sink.
- The input voltage must be approximately 2.5 V above the output voltage in order to maintain regulation.
- The circuits have internal thermal overload protection and short-circuit current-limiting features.
- Thermal overload occurs when the internal power dissipation becomes excessive and the temperature of the device exceeds a certain value.
- Almost all applications of regulators require that the device be secured to a heat sink to prevent thermal overload.



FIXED NEGATIVE LINEAR VOLTAGE REGULATORS

- The 79XX series is typical of three-terminal IC regulators that provide a fixed negative output voltage.
- This series is the negative-voltage counterpart of the 78XX series and shares most of the same features and characteristics except the pin numbers are different than the positive regulators.

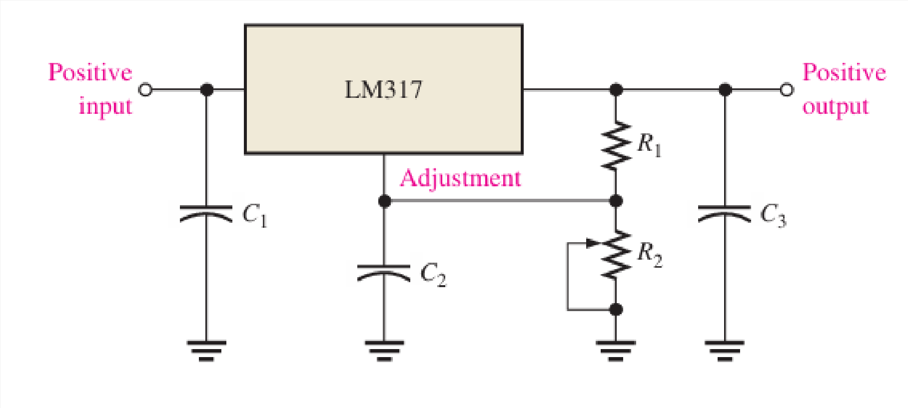


(a) Standard configuration

Type number	Output voltage
7905	–5.0 V
7905.2	–5.2 V
7906	–6.0 V
7908	–8.0 V
7912	–12.0 V
7915	–15.0 V
7918	–18.0 V
7924	–24.0 V

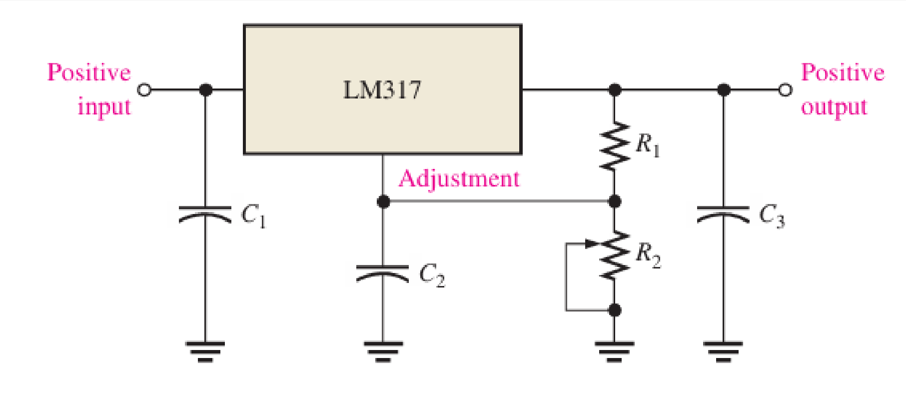
ADJUSTABLE POSITIVE LINEAR VOLTAGE REGULATORS

- The LM317 is an example of a three-terminal positive regulator with an adjustable output voltage.
- The capacitors are for decoupling and do not affect the DC operation.
- There is an input, an output, and an adjustment terminal in this type of regulator.
- The external fixed resistor R_1 provide the output voltage adjustment.
- V_{OUT} and the external variable resistor R_2 can be varied from 1.2 V to 37 V depending on the resistor values.
- The LM317 can provide over 1.5 A of output current to a load.



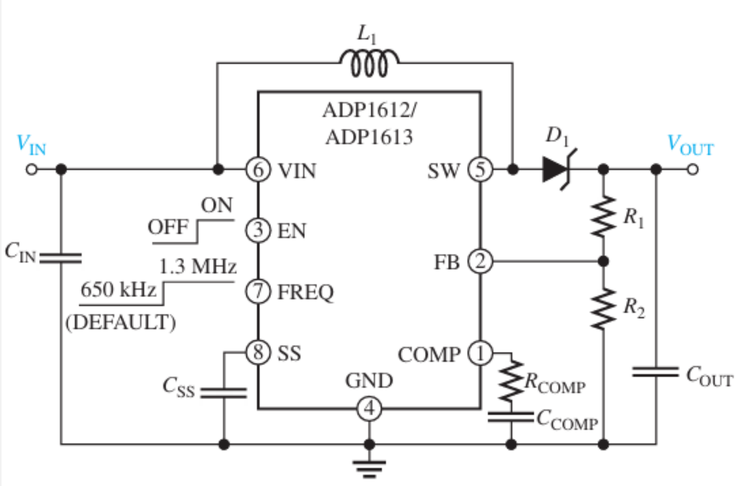
ADJUSTABLE NEGATIVE LINEAR VOLTAGE REGULATORS

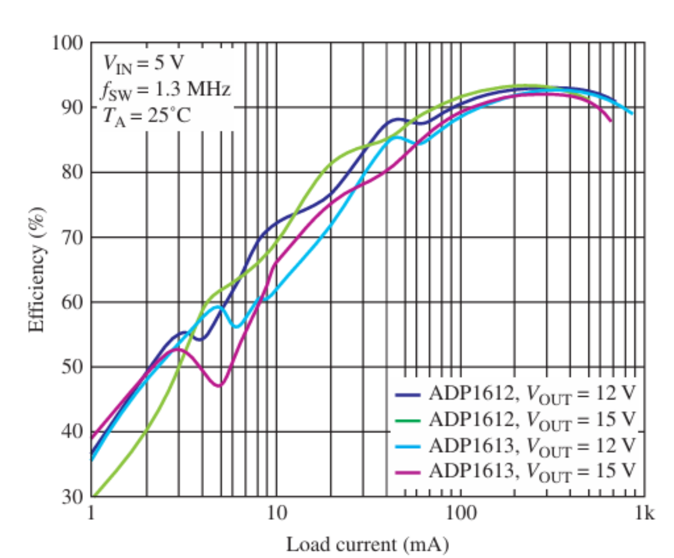
- The LM337 is the negative output counterpart of the LM317 and is a good example of this type of IC regulator.
- Like the LM317, the LM337 requires two external resistors for output voltage adjustment.
- The output voltage can be adjusted from $-1.2\ V$ to $-37\ V$, depending on the external resistor values.
- The capacitors are for decoupling and do not affect the dc operation.



SWITCHING VOLTAGE REGULATORS

- **The Step-Up Switching Regulator**
  - The step-up regulator configuration using an ADP1612/ADP1613 is shown in the Figure.
  - The ADP1612 and the ADP1613 are essentially the same except for their switching frequency, which is used in the pulse-width modulation (PWM) operation.
  - This regulator operates with PWM and exhibits an efficiency of up to 94% at the higher switch frequency, depending on the output current and voltage.
  - The load current increases, the efficiency increases.
  - The output voltage has a much smaller effect.
  - The operating frequency of the PWM is pin-selectable for 650 kHz or 1.3 MHz.
  - The lower frequency results in better efficiency, and the higher frequency allows the use of smaller external components.





SWITCHING VOLTAGE REGULATORS

- **The Step-Down Switching Regulator**
  - The step-down regulator configuration using an ADP2300/ADP2301 is shown in the Figure.
  - The ADP2300 and the ADP2301 are essentially the same except for their switching frequency.
  - Unlike the ADP1612/ADP1613, this device does not have pin-selectable frequencies. Instead, each has a fixed internal oscillator.
  - This regulator operates with PWM and exhibits an efficiency of up to 91%, depending on the output current.
  - This device has thermal shutdown (TSP) protection in case temperature exceeds 140°C and turns back on when the temperature drops to 150°C.
  - Also, it has an under-voltage lock-out (UVLO) feature and short-circuit protection.
  - As the load current increases above about 0.2 A, the efficiency remains relatively constant (between about 91% and about 88%) and drops off a little as the output current increases.